Probing Cosmic Ray Composition and Muon-philic Dark Matter using GeV Muon sources

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Introduction

- Main focus of this talk is this recently published paper:

PHYSICAL REVIEW LETTERS **136,** 151001 (2026)

Probing Cosmic Ray Composition and Muonphilic Dark Matter via Muon Tomography

Cheng-en Liu, Rongfeng Zhang, Zijian Wang, Andrew Michael Levin, Leyun Gao, Jinning Li, Minxiao Fan, Youpeng Wu, Zibo Qin, Yong Ban, Zaihong Yang, Qite Li,[*] Chen Zhou,[†] and Qiang Li[‡]

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- Use sea-level (secondary) cosmic muons as “free” muon source
- Study cosmic-ray composition and search for dark matter (DM)
- Here DM is the “target”, reverse of well-known DM experiments

My collaborators

Theoretical background

McKeen, Morrissey, Pospelov, Ramani, and Ray
PRL 2023

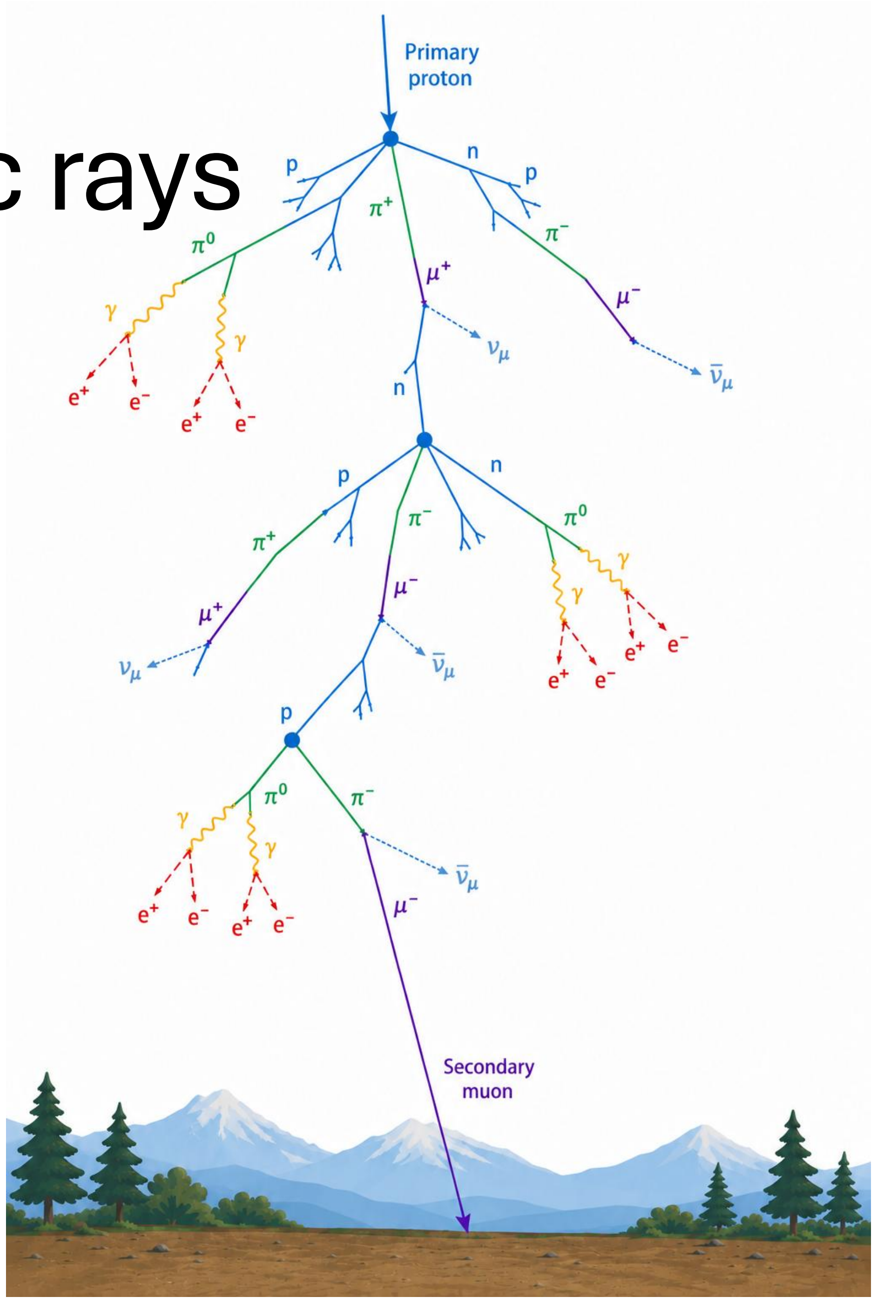
Upon thermalizing in the Earth's environment, the χ phase space is drastically modified compared to the virialized galactic population. In particular, the loss of kinetic energy typically implies a significant enhancement to the local terrestrial density. For instance, since χ's thermal velocity $v_{\rm th} \sim \sqrt{300\ \mathrm{K}/m_\chi} \sim 5 \times 10^{-6}\sqrt{1\ \mathrm{GeV}/m_\chi}$ is well below the Earth's escape velocity $v_{\rm esc} \simeq 4 \times 10^{-5}$ for $m_\chi \gg 1$ GeV, such particles remain gravitationally bound as a hydrostatic gas, accumulating over the entire age of the Earth $t_\oplus \simeq 4.5$ Gyr to extremely large densities [8].

Berlin, Liu, Pospelov, and Ramani
PRD 2024

Owing to their interactions with ordinary matter, a strongly interacting dark matter component (DMC) would be trapped readily in the Earth and thermalize with the surrounding matter. Furthermore, for lighter DM, strong matter interactions allow Earth-bound DM particles to distribute more uniformly over the entire volume of the Earth rather than concentrating near the center. Together, this can make the DM density near the surface of the Earth tantalizingly large, up to $\sim f_\chi \times 10^{15}\ \mathrm{cm}^{-3}$ for DM mass of 1 GeV [8–11]. Despite their large surface abundance, such

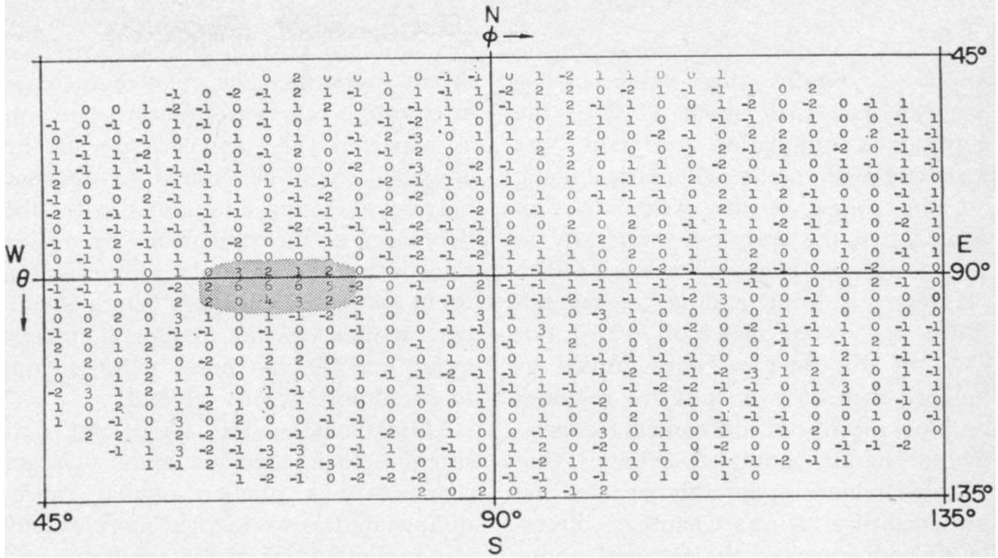
Primary and secondary cosmic rays

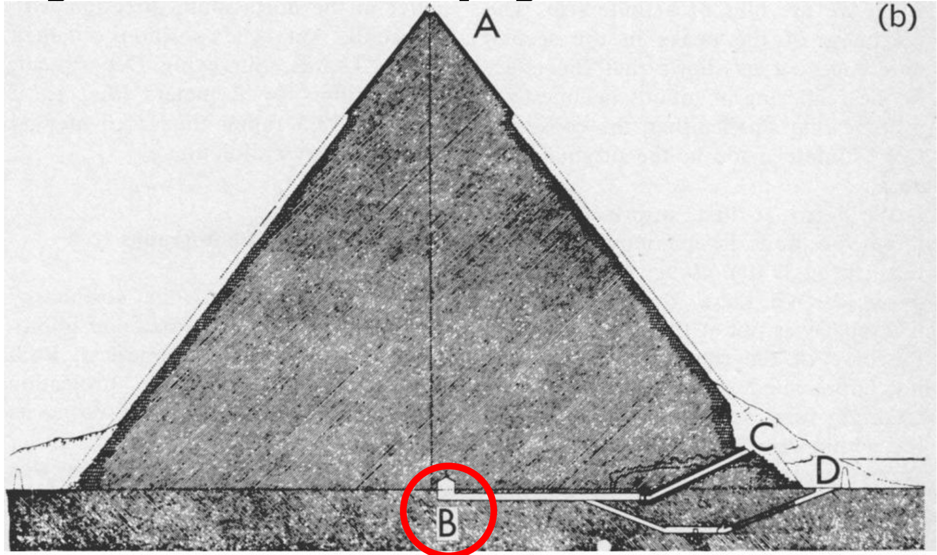
- Primary cosmic rays are mostly protons and alpha particles
- Luckily for humans, these particles almost never make it through the atmosphere
- Through interactions in the atmosphere, primary cosmic rays transfer their energy to secondaries including electrons, muons, and pions

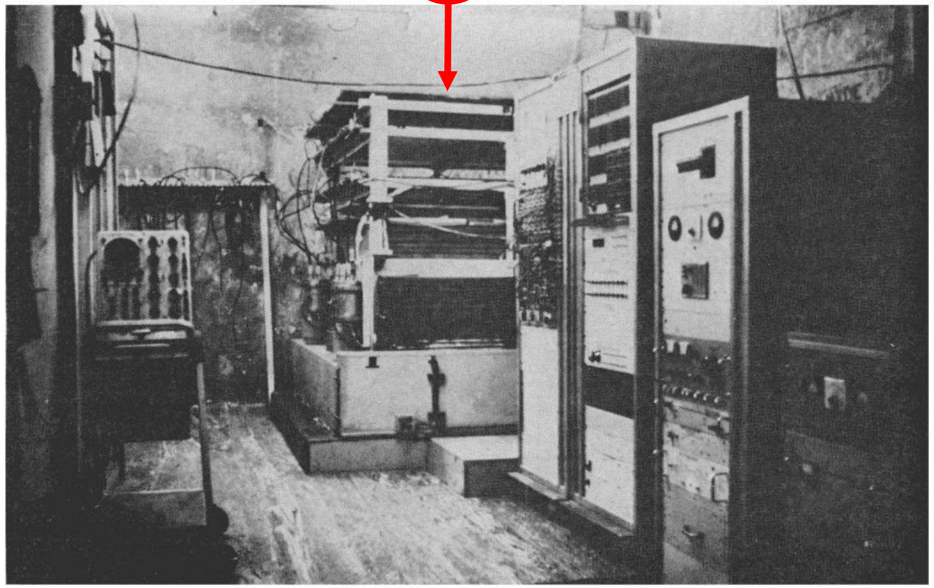


Cosmic muon “tomography” at the pyramids

- There is a long history of using (secondary) cosmic ray muons as a “free” muon source:
- [Science 1970](#) **Search for Hidden Chambers in the Pyramids**

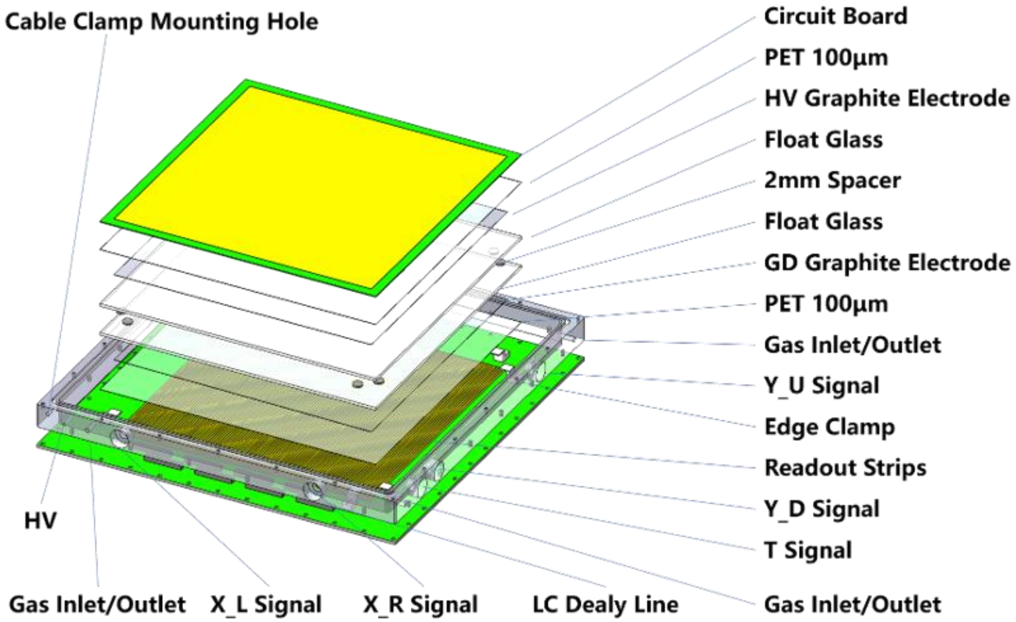




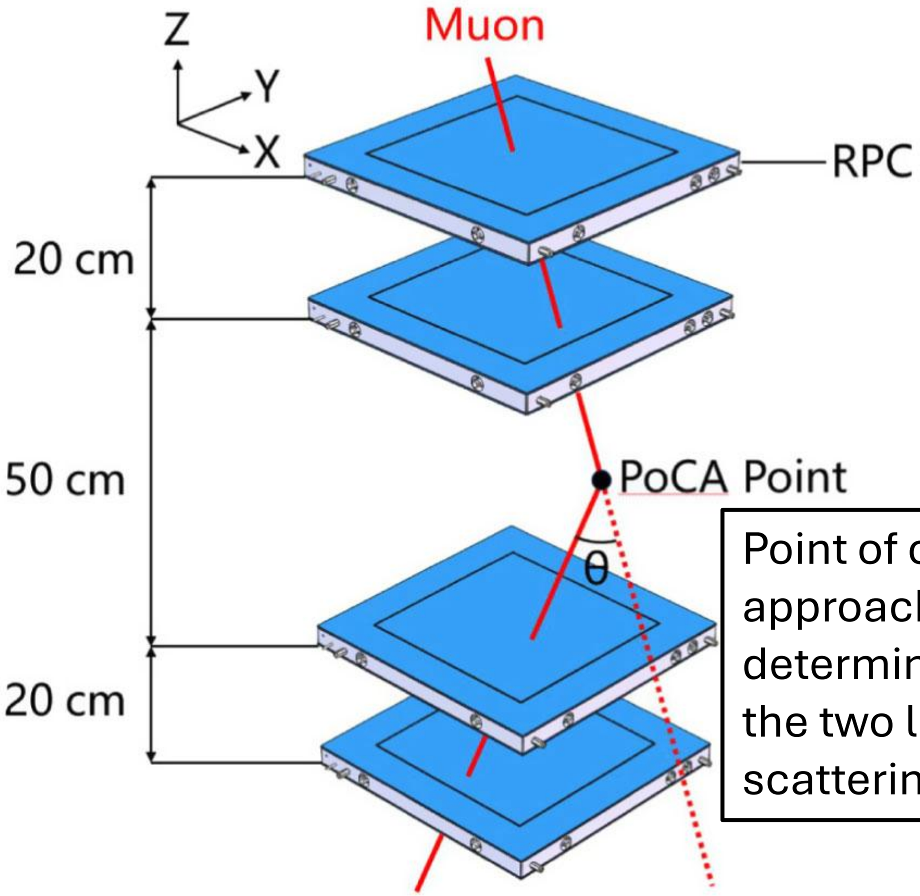


Resistive plate chamber (RPC) technology

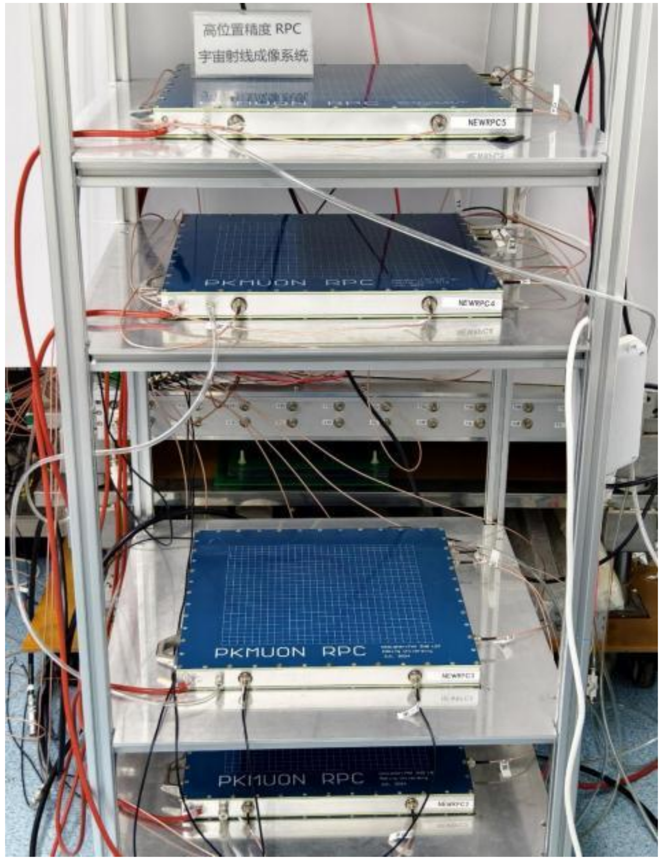
- Similar RPC technology is used in CMS to provide triggering information
- Chamber filled with pure R-134a ($C_2H_2F_4$) gas
- Provides time and position
- Obtain two-dimensional position information with two orthogonal readout strip layers



Experimental setup



Point of closest approach (PoCA point) determined between the two lines to define scattering angle

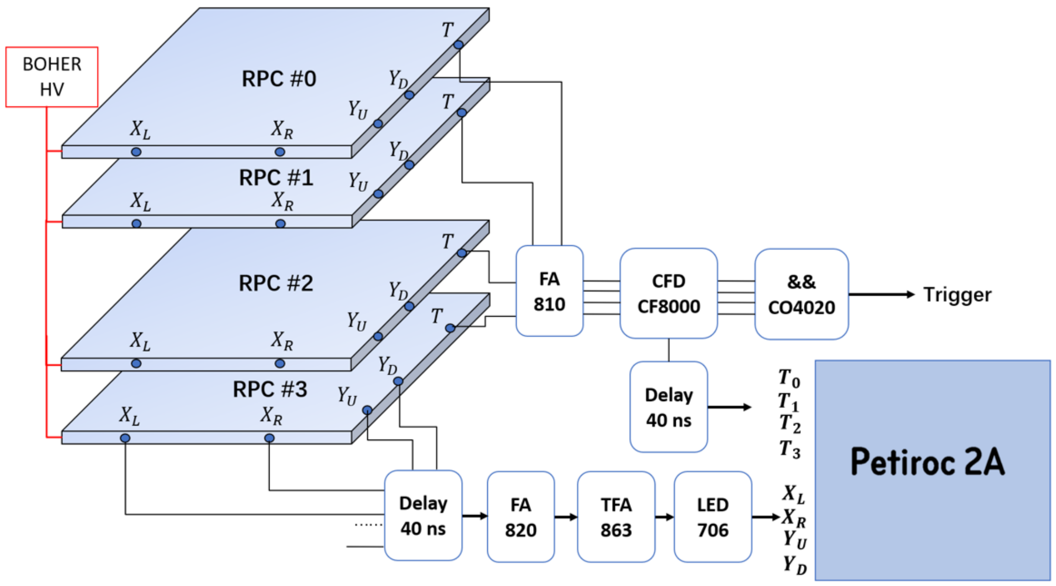


Resolution and reconstruction efficiency

- The position resolution and reconstruction efficiencies were studied extensively in our previous works
  - Nucl. Instrum. Methods Phys. Res., Sect. A 663, 22 (2012)
  - Chin. Phys. C 37, 016002 (2013)
  - Phys. Rev. D 110, 016017 (2024)
- The reconstruction efficiency is around 85% for a single RPC chamber, corresponding to 54% for four RPC chambers
- The spatial resolution is 0.7 mm

Read-out electronics and data acquisition

- Main components are PCBs attached to detectors, off-detector amplifier-comparator boards, a Petiroc ASIC, and a PC
- Raw detector signals pass through hardware-based coincidence trigger before being written to disk

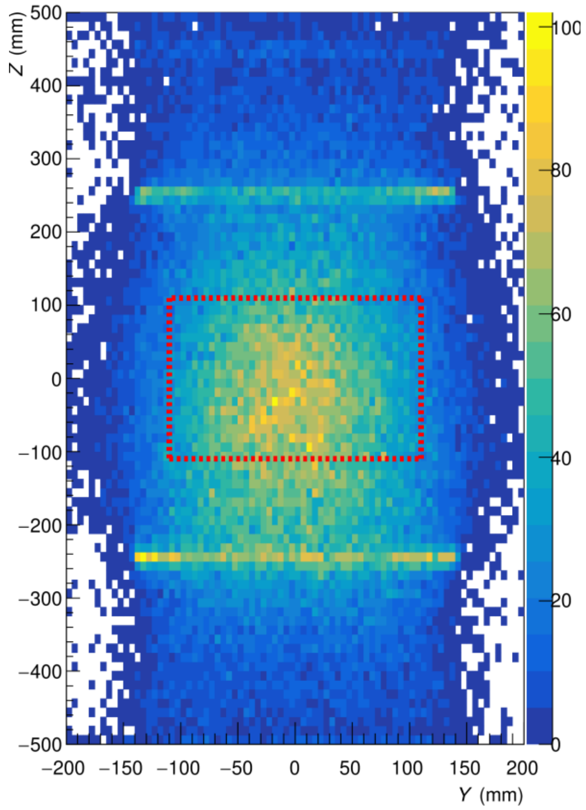


Simulation

- CRY for (secondary) cosmic ray generation
  - Input precise latitude and longitude of Peking University
  - Difference between sea-level and Beijing elevation (44 m) neglected
  - Sea-level (secondary) cosmic ray muon flux is ~1/60 s^{-1} cm^{-2} and mean energy is 3-4 GeV
- GEANT4 for particle transport and detector simulation
  - Detailed detector geometry description
  - Simulates interactions of particles with metal, plastic, gas, air, etc.
- Interaction between muon and dark matter modeled as classical elastic scattering

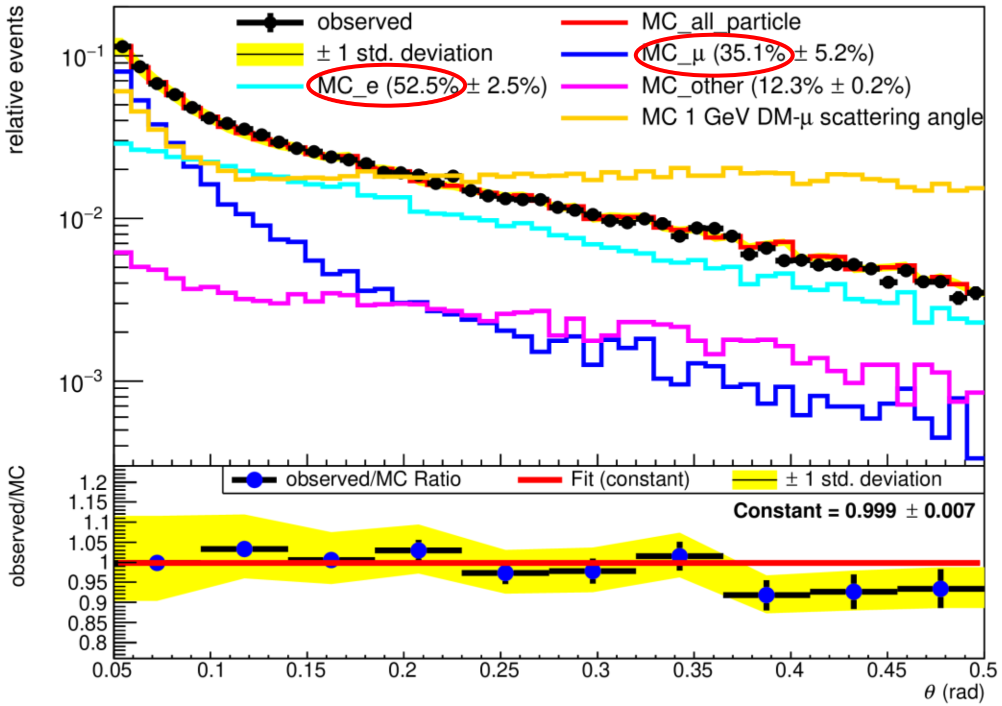
Data-taking

- Fiducial volume is a cube with side length 220 mm around center of apparatus (in red)
- 63 days of data-taking, starting on February 12, 2025
- 1.18 million triggered events were collected
- Scatter plot of the (x,y) position point of closest approach shown on the right



Secondary cosmic ray composition results

- Binned maximum likelihood fit of electron and muon fractions
  - Floating electron component
  - Floating muon component
  - Fixed other component
- Fit performed between 0.05 and 0.5 radians
- Excellent agreement with simulation with no dark matter

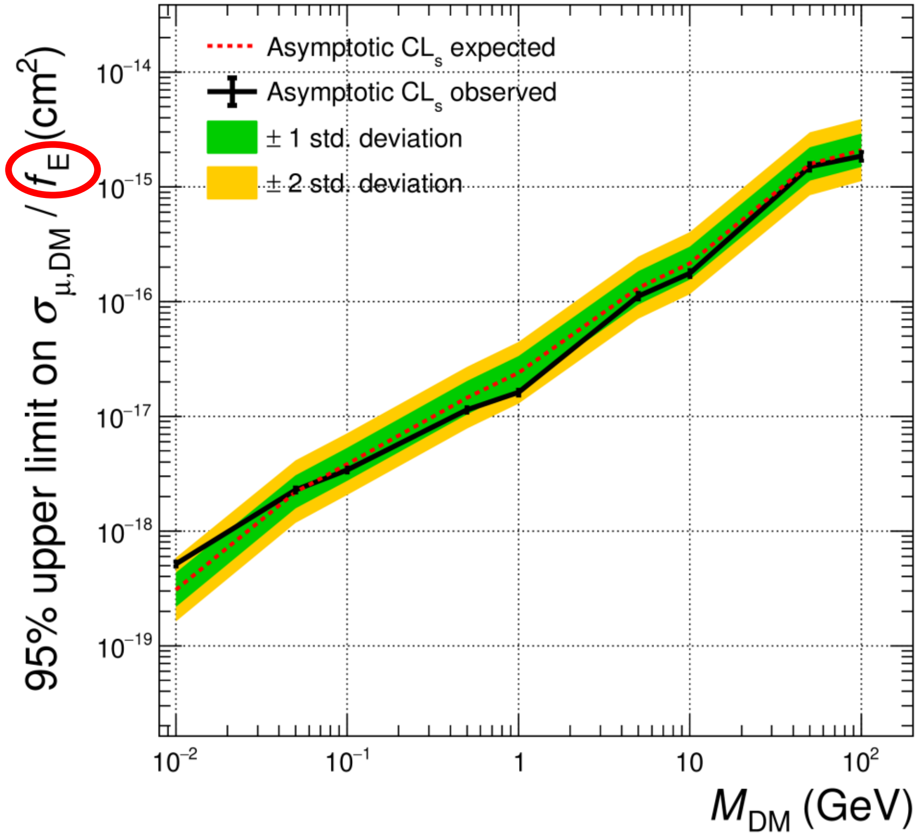


Systematic uncertainties

- Systematic uncertainties were evaluated by varying the subset of data fit and the fit strategy
  - Fit smaller angular range: 0.1 to 0.35 radians instead of 0.05 to 0.5 radians
  - Fit smaller fiducial volume: $x, y, z \in$ (-100 mm,100 mm) instead of $x, y, z \in$ (-110 mm,110 mm)
  - Perform three component (electron, muon, other) instead of two component (electron, muon) fit
- Final overall systemic uncertainty for muon fraction is around 20%

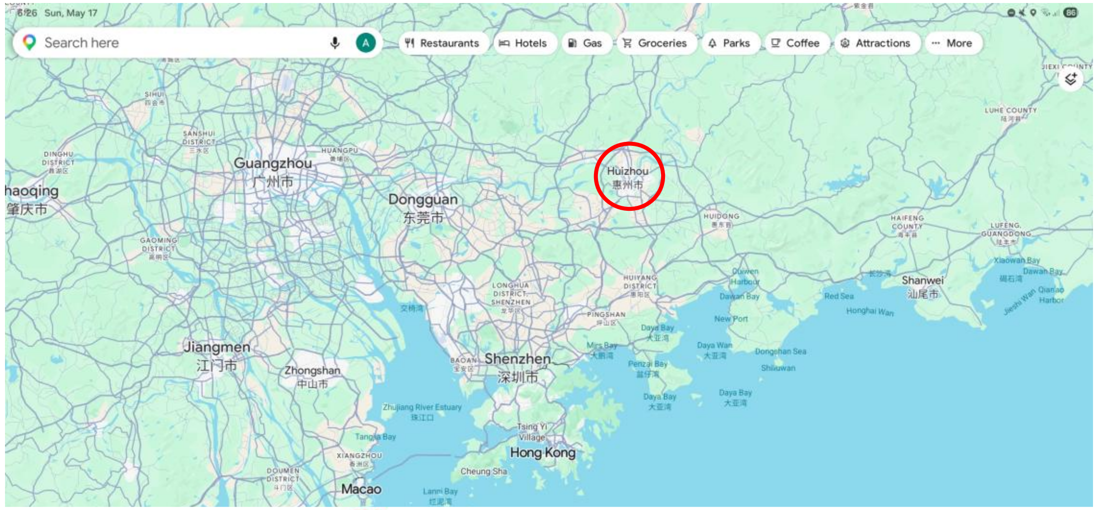
Dark matter results

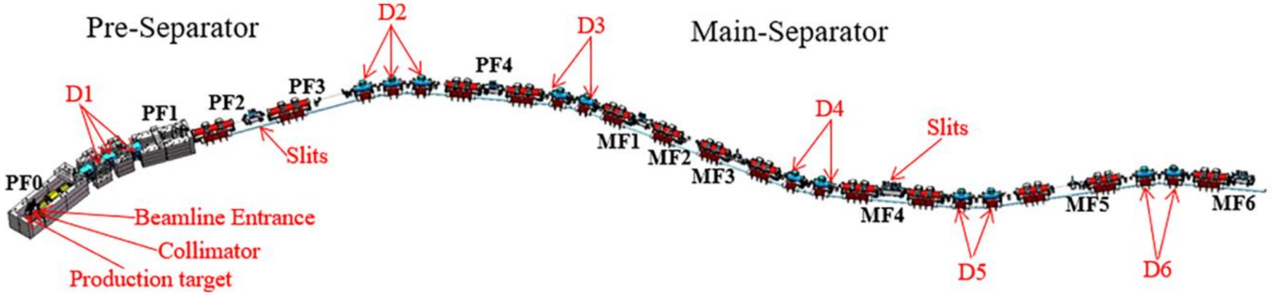
- Fit same data as before, but now floating DM component added to the other three
- Calculated using the CMS Higgs Combination tool with the asymptotic approximation
- Separate fit for each DM mass
- DM density is ρ=0.3 GeV/cm^3 times “enhancement factor” f_E, set to 10^{15}



Accelerator-based version

- Accelerator-based version of same setup is natural next step
- Experiment could be conducted at HIAF HIRIBL in Huizhou, China
- The HIAF HIRIBL accelerator generates high intensity tunable 1-10 GeV muon beams
- Phys. Rev. D 113, 072008, published on April 13, 2026, contains related study





Conclusions

- PKMu is a proof-of-concept experiment to study (secondary) cosmic ray muons and test a thermalized dark matter hypothesis
- For a 1 GeV dark matter candidate, the 95% confidence level upper limit on the scattering cross section is 1.62×10^{-17} cm^2, assuming a dark matter density enhancement factor 10^{15}
- The observed data and analysis code are publicly available
- Next iteration of the experiment will likely use high-intensity accelerator muon beam instead of cosmic rays

Backup